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Methods of reducing crop variation in apple trials

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SUMMARY

Data are examined from an apple trial over a period of sixteen years during which the trees received no differential treatments. Crops for a varying number of years were accumulated in order to determine how long a period is needed to obtain a low coefficient of variation. Four years were better than two, but six years gave little advantage over four. Covariance by previous crops was useful, two years' crop being as good as four years' crop. Adjustment by trunk girth was less successful but could be recommended in conjunction with previous crop. Number of fruits was a more variable record than crop weight. Removing positional variation by analysis of variance did not have a major effect in reducing variation. Where space is available multi-tree plots proved effective since adjacent tree crops are not highly correlated, but covariance adjustment of multi-tree plots was not successful.

In conducting a field trial material and land are carefully selected to minimize variation not due to treatments. Past experience guides those designing the trials in such matters as the number of replicates and plants per plot needed to show an expected difference in treatment means. With perennial crops there are additional considerations. Treatments may be confined to one year but usually they or their effects extend over an indefinite number of years. If the experimenter decides to start with new material he may use young trees whose cropping is more erratic than mature trees. Alternatively, he may use older trees that have a past history, probably of differential treatments that have increased variation between trees.

With mature trees it is often assumed that there is considerable scope for using past crops and measures of tree size in the form of trunk girths to make allowances for variation in future cropping. Another method of reducing variation is to accumulate crops over a number of years, smoothing out year-to-year variation. Both methods may be used together with advantage but the experimenter may find that the trial is extending over a greater length of time than is desired. This paper explores the relative merits of applying different policies of covariance adjustment and crop accumulations.

DATA USED

The orchard was planted in February 1951 as one-year-old trees, 5·4×5·4 m apart. There were 54 trees each of Cox's Orange Pippin and Worcester Pearmain, both on rootstock M.7. The habits of the two cultivars differ; Cox produces most of its flowers and fruit on spurs, whereas Worcester is mainly a tip-bearer producing most of its fruit on one-year wood. Cox shows a greater tendency to branch than Worcester and generally produces larger trees.

The trees were planted in six rows of 18 trees, with an additional guard row on each side. Arrangement from west to east was: single guard row of Worcester, three rows of Cox, three rows of Worcester and a single guard row of Cox. No differential treatments were applied. All trees were deblossomed in 1952 and the first crop occurred in 1953. This consisted of on average two or three fruits per tree with some trees not fruiting. The distribution of fruit number was markedly skew and is therefore not considered in this study. The 1954 crop for Cox was about 4 kg, that for Worcester only two-thirds this. Their distributions were then more symmetrical but showed some tendency to be bimodal. Whether the distribution is made up of a mixture of two populations is an open question but Moore (1962) has shown that sometimes a planting of clonal apples can be separated into two groups. In 1955 the mean crop weight for Cox was about 8 kg and that of Worcester about half that. The distributions were then more or less symmetrical although somewhat too flattened at the mode to be a good fit to the normal distribution. The distribution of later crops appeared to approximate well to that of the normal distribution.

Total crop weight and number of fruits were recorded annually up to 1965; the crop weight record was then carried on for a further two years. Throughout, all trees were recorded individually and the results discussed below have been computed on individual trees, unless otherwise stated.

RESULTS

Relative merits of accumulating crop and covariance

Results for Cox's Orange Pippin are summarized in Table I and those of Worcester Pearmain are summarized in Table II. Coefficients of variation are shown, as it is variation relative to the mean that is usually important, rather than standard errors.

Worcester is less variable than Cox, giving coefficients of variation that average about two-thirds those of Cox. The pattern of variation within each cultivar is very similar. Early crops are more variable than later ones. Accumulating crops or adjusting by earlier crops reduces variation. Generally in the earlier years accumulation of crops is better than covariance; whereas, in later years covariance is better. In many cases waiting a year before applying treatments, so that covariance can be used, appears to be the best policy; this is particularly so with Worcester. However there are dangers; note the high coefficients of variation of 55% for Cox crop 1959 adjusted by 1958. That for accumulated crop 1958+1959 is only 23%.

When crop records over four years are available accumulation of the crop over the whole period is clearly not as good as splitting the period and adjusting the sum of the two latter years by double covariance using the two earlier years. Only on one occasion was accumulation better with Cox and on no occasion was it better with Worcester.

If a six-year period is available there are numerous possibilities for accumulating and adjusting crops. The three included in this study are as follows:

TABLE I

Coefficients of variation (%) of Cox crop weight accumulated from 1–6 years and adjusted by covariance using previous crops and trunk girth

No. of years accum. crop	Records used for covariance adjustment	Total No. of years crop involved	Final year of period considered												
			1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967
1	No adjustment	1	53	33	25	25	55	21	26	25	21	15	21	15	23
2	No adjustment	2	41	34	22	22	23	22	18	21	20	16	15	15	14
4	No adjustment	4			22	20	19	19	18	19	17	17	16	13	13
6	No adjustment	6					19	17	16	17	18	16	15	14	14
1	Previous crop	2	50	26	25	21	55	21	25	24	17	13	20	13	23
2	Previous crop	3	41	30	20	20	19	21	17	20	19	11	14	13	13
4	Previous crop	5				18	18	18	16	18	17	15	14	9	11
6	Previous crop	7					18	15	15	16	15	15	15	13	13
1	Two previous years' crops	3	50	25	25	21	51	15	23	22	16	11	20	13	23
2	Two previous years' crops	4		30	19	20	19	20	14	18	16	10	12	13	13
4	Two previous years' crops	6				17	17	17	16	18	14	15	13	9	10
6	Two previous years' crops	8						15	15	17	16	15	12	13	12
1	Sum of four previous years' crops	5			25	23	57	20	26	22	18	12	20	12	22
2	Sum of four previous years' crops	6				21	21	21	16	20	17	13	13	13	12
4	Sum of four previous years' crops	8						18	17	18	15	15	13	11	10
6	Sum of four previous years' crops	10								16	16	15	13	13	12
1	Trunk girth	1	53	33	24	18	56	17	25	24	19	13	22	14	24
2	Trunk girth	2		34	21	17	21	21	14	20	18	14	15	15	14
4	Trunk girth	4					17	15	15	17	14	14	15	13	12
6	Trunk girth	6						14	14	14	14	14	13	13	13
1	Trunk girth + 4 years' crops	5			24	17	57	17	26	22	17	12	18	12	22
2	Trunk girth + 4 years' crops	6				17	20	21	13	19	16	12	13	13	12
4	Trunk girth + 4 years' crops	8						15	15	17	12	14	13	11	10
6	Trunk girth + 4 years' crops	10								14	13	14	12	12	12

TABLE II

Coefficients of variation (%) of Worcester crop weight accumulated from 1–6 years and adjusted by covariance using previous crops and trunk girths

No. of years accum. crop	Records used for covariance adjustment	Total No. of years crop involved	Final year of period considered												
			1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967
1	No adjustment	1	37	33	21	16	19	23	14	21	15	15	15	16	17
2	No adjustment	2	32	27	21	15	17	17	17	16	15	14	14	14	15
4	No adjustment	4		24	20	14	14	15	15	15	14	14	14	13	14
6	No adjustment	6				14	13	14	14	15	14	14	14	13	13
1	Previous crop	2	34	32	19	12	12	17	11	15	14	10	12	12	10
2	Previous crop	3	32	25	20	14	13	13	10	10	8	12	10	10	11
4	Previous crop	5			20	14	14	15	14	12	9	11	8	11	11
6	Previous crop	7					13	14	14	15	14	10	9	10	8
1	Two previous years' crops	3	33	32	19	12	9	17	9	13	11	10	12	11	10
2	Two previous years' crops	4		25	20	14	13	13	10	9	8	9	9	10	10
4	Two previous years' crops	6				14	14	15	14	12	10	9	8	9	11
6	Two previous years' crops	8						14	14	15	14	10	9	9	8
1	Sum of four previous years' crops	5			19	13	12	20	9	14	13	11	11	12	10
2	Sum of four previous years' crops	6				14	14	15	13	10	9	11	10	10	11
4	Sum of four previous years' crops	8						15	14	14	11	9	8	10	10
6	Sum of four previous years' crops	10								15	14	12	10	9	8
1	Trunk girth	1	37	33	20	11	11	19	9	19	10	11	13	14	16
2	Trunk girth	2		27	20	12	10	13	11	12	10	9	10	12	13
4	Trunk girth	4					12	11	10	12	9	8	9	9	11
6	Trunk girth	6						13	12	11	9	9	8	8	9
1	Trunk girth + 4 years' crops	5			17	9	10	19	8	14	10	10	11	12	10
2	Trunk girth + 4 years' crops	6				10	8	12	11	10	9	9	9	10	11
4	Trunk girth + 4 years' crops	8						11	10	11	9	7	8	8	10
6	Trunk girth + 4 years' crops	10								12	9	9	8	7	8

(i) accumulation of crop for six years, no covariance adjustment;
(ii) accumulation of crop for four years, adjustment by previous two years;
(iii) accumulation of crop for two years, adjustment by accumulated crop of previous four years.

Accumulation of crop for six years with no covariance adjustment was not as effective as accumulation of crop for two or four years using covariance. This is especially true in the later years. Accumulation of crops for four years and adjustment by the previous two was definitely better than the reciprocal arrangement of adjusting two years' crop by the accumulation of the previous four years.

Very little advantage was obtained by using ten years' records, i.e. accumulating six years' crop and adjusting by the previous four years' crop. Comparing this method with a two-year unadjusted crop total shows only a reduction in coefficient of variation of 1 or 2% for Cox. For Worcester there is a similar, small reduction, except in the later years where coefficients of variation are substantially lower using a ten-year crop.

Use of trunk girth as a covariate

Trunk girth is well correlated with tree size, so its use as a covariate might be expected to reduce variation in cropping due to differences in tree size. The results of adjustment by girth recorded in the year previous to the start of the cropping period and also by double covariance using crop accumulation for four years as an additional covariate to that of girth are shown in Tables I and II.

The addition of trunk girth as a covariate results in only small reductions in variation, usually reducing the coefficients of variation of Cox by 1 or 2%; the reductions for Worcester are a little better, girth in later years was quite effective in reducing variation of four and six years' crops. Coefficients are further slightly reduced by the use of the accumulated crop of the previous four years as an additional covariate.

The reductions are not as great as those previously obtained by Pearce and Brown (1960). This may well be for the reason suggested by these authors; namely, that the better calibrating record is the one that measures the dominant activity. Thus if the trees are growing well but cropping poorly then trunk girth is likely to be a good calibrating variate, but if the trees are cropping well, as is the case here, trunk girth is likely to be poor relative to previous crop as a covariate.

The effect of positional variation

The 54 trees of each cultivar were planted as three rows each with eighteen trees. Since the site appeared uniform, the most reasonable way to allow for positional variation would seem to be to remove the effects along and across rows. Results from some of the analyses are presented in Table III as the differences between the coefficient of variation computed from the total variation and that computed from variation remaining after removal of the sum of squares associated with positional variation.

The small negative values shown in Table III arise because the amount of variation along and across rows is less than the average amount of the total variation associated with a single degree of freedom. In the case of Worcester there are numerous small negative

TABLE III

Difference between coefficient of variation computed from the total variations and that remaining after removal of variation due to blocks
(Total–error)

	One or two years starting from	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966
COX	One year unadjusted	10	3	2	7	3	2	2	3	4	2	3	1
	One year adjusted by girth and four-year crop			1	0	6	−2	1	2	5	3	1	0
	Two years unadjusted	5	2	6	4	1	1	2	3	2	2	1	2
	Two years adjusted by girth and four-year crop			1	1	1	−2	1	2	2	3	0	1
WORC.	One year unadjusted	1	6	1	0	−1	2	−1	−2	−1	−2	0	0
	One year adjusted by girth and four-year crop			3	0	2	2	1	−1	2	0	3	2
	Two years unadjusted	2	1	−1	−1	0	1	−1	−1	−2	−2	−1	−2
	Two years adjusted by girth and four-year crop			0	−1	1	2	0	1	1	1	4	2

values and, although the average is positive, they do indicate the very small effect of blocking in reducing variation. Blocking has been a little more successful with Cox, variation being reduced on average by about 2%.

With a single year's crop and to a lesser extent with two years' crop, removal of positional effects has been reasonably successful. For Cox covariance adjustment by previous crop and trunk girth greatly reduces the usefulness of removing positional variation. This does not seem to be the case with Worcester where the small negative values in Table III have been converted to small positive ones by the use of covariance. However, there seems to be so little positional variation with Worcester that no definite conclusions can be drawn from the behaviour of this cultivar for the interaction of covariance and positional variation.

The use of multi-tree plots

Accumulating crop over years has been considered in some detail; a logical alternative is to accumulate crop from adjacent trees, i.e. use multi-tree plots. A reduction in error can be expected but is obtained at the expense of using more land and trees. How much larger the trial needs to be will depend on the degree of correlation between adjacent plots. Where there is good correlation a considerable increase in the number of trees will be needed to increase the accuracy of the experiment; where there is little or no correlation between adjacent trees then multi-tree plots may be only a little less efficient than single-tree plots.

In order to study the effects of amalgamating neighbouring plots, the crop for three periods of four years has been used, the early years 1954–57, middle years 1958–61 and the later years 1962–65. The results for one- to six-tree plots are shown in Table IV. The two later periods are also shown adjusted by the previous four years' crop. The figures in parentheses adjacent to the unadjusted values are the theoretical results assuming zero correlation between adjacent trees. The theoretical results have been deduced by dividing the coefficient of variation for one-tree plots by the square root of the number of trees in each multi-tree plot.

For purposes of comparison two-tree plots for four years, "8 tree-years", can be compared with using a four-year period adjusted by the previous four years (Tables I

TABLE IV

Coefficients of variation of crop weight from multi-tree plots. Values in parentheses are theoretical values computed from 1-tree plots by dividing by the square root of the number of trees per plot

Cultivar	Number of trees per plot	Four-year periods 1954–57	1958–61		1962–65		Twelve years 1954–65
		unadjusted	unadjusted	adjusted	unadjusted	adjusted	
COX	1	22	17	17	16	13	14
	2	19 (16)	12 (12)	12	10 (11)	9	10 (10)
	3	15 (13)	12 (10)	12	10 (9)	8	10 (8)
	6	13 (9)	8 (7)	8	8 (7)	8	8 (6)
WORC.	1	20	15	14	14	8	13
	2	16 (14)	11 (11)	11	10 (10)	7	10 (9)
	3	12 (12)	11 (9)	11	10 (8)	5	10 (8)
	6	10 (8)	11 (6)	11	8 (6)	3	9 (5)

and II). In the case of Cox there appears to be an appreciable advantage in using two-tree plots but the comparison is less clearly in favour of two-tree plots for the Worcester trees.

Covariance adjustment of the middle period 1958–61 by the first four years' crop has been very disappointing. There has been some success with Worcester in using the middle period to adjust the later period 1962–65, particularly for six-tree plots where the coefficient of variation has been reduced to the remarkably low figure of 3%. However, it must be remembered that this has been obtained by using six trees per plot for four years adjusted by a previous four years, i.e. it involves 48 "tree-years" per plot, hardly efficient even when compared to coefficients of variation of about 30% for single-tree plots within one year.

Comparison of crop weight and crop number

All the computations performed on crop weight of individual trees were repeated on number of fruits. The results of the two sets of analyses are very similar, but nearly always variation in fruit number is a little greater than that of crop weight. Only analyses of single and two years' crops unadjusted and adjusted by trunk girth and crop over four years are shown in Table V. Results are expressed as differences between coefficient of variation of fruit number and coefficient of variation of fruit weight.

Once again there are greater differences for Cox than for Worcester. Generally, Worcester fruit number is more uniform than Cox fruit weight, especially for crop over two years. Differences between weight and number are smaller for crop accumulated over two years than for a single year's crop. This trend is continued with four- and six-year periods. Comparison of six-year accumulations of crop weight and number show a difference between coefficients of variation of about ½% on average as against about 5 and 2% for a single year's Cox and Worcester crop respectively.

DISCUSSION

Variation of apple tree crops has been described by Pearce (1949). Early crops were more variable than later ones, requiring about ten years for variation to settle down. Covariance adjustment of later crops by previous ones reduced variation by a quarter; trunk girth was less effective. These studies were taken further by Pearce and Brown (1960). Using a double covariance by trunk girth and previous crop, error variance was reduced by half.

The present trial was started in an attempt to understand the method by which variation starts and builds up within an orchard. Results from the earlier years were studied by Moore (1965); tree vigour was found to be correlated from year to year but this correlation decayed with time; in particular nursery vigour was little associated with field vigour. Fruitfulness independent of vigour was not well related from year to year. Clarke (1967), working at Long Ashton, found that covariance was more effective with the relatively uniform cultivar Worcester than with the much more variable Cox. Thus it must be concluded that covariance adjustment, although an important method in reducing variation, is not likely to remove more than half the variation, still leaving coefficients of variation of about 20% or more for annual crop weight from single-tree plots.

TABLE V

Difference between coefficients of variation computed from crop weight and that computed from number of fruits
(Number–weight)

	One or two years starting from	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965
COX	One year unadjusted	6	4	2	0	18	3	6	5	5	0	2
	One year adjusted by girth and four-year crop			3	3	15	3	8	7	6	1	3
	Two years unadjusted	4	2	−1	−1	2	0	2	4	1	0	
	Two years adjusted by girth and four-year crop			1	0	2	3	4	4	2	1	
WORC.	One year unadjusted	1	0	2	2	−1	5	3	5	2	3	4
	One year adjusted by girth and four-year crop			1	2	−1	5	3	5	2	2	4
	Two years unadjusted	1	1	2	0	0	2	3	3	2	2	
	Two years adjusted by girth and four-year crop			1	2	0	2	2	2	2	2	

At East Malling it has often been found that blocking treatments has not reduced variation by as much as was hoped. Results reported here concerning a fairly simple blocking structure confirm this belief. Other much more complicated blocking structures were also applied to the data without any further substantial reduction in variation. On a variable site blocking is of the utmost importance, but the trees studied in this paper were planted in a good uniform soil and under such conditions it is unlikely that further reductions in variation of apple tree crops will be brought about from a continued pursuit of either improved blocking structures or more complex covariance based on measures of previous crop or tree size. It would be better to explore the accumulation of crops either from adjacent trees, i.e. multi-tree plots, or by accumulating crop over a number of years.

If cropping patterns were stable it might well be assumed that adjustment of crop over six years by the previous four years' crop and trunk girth would considerably reduce variation. This is only partially so. Thus for accumulated crop weight over six years, the mean coefficient of variation for unadjusted crop is 16% whereas the same record adjusted by both trunk girth and crop accumulated over the previous four years is 13%. The corresponding figures for Worcester are 14 and 9.

It appears that cropping patterns are less marked but more stable for Worcester than for Cox. Worcester is not only more uniform than Cox; it is also more amenable to calibration by covariance prior to the application of experimental treatments.

The tendency with apples has been to work with single-tree plots. This is because, with a given area of land, the smallest error variance is obtained by using the smallest possible plots, i.e. single plants. The reason for this is that adjacent trees are likely to be correlated, resulting in the standard error of multi-tree plots not being reduced proportionally to the square root of the number of trees per plot. With increasing use of very small trees there is a tendency to design more experiments using multi-tree plots, and research workers such as Terts (1973) are starting to reconsider the variation associated with multi-tree plots. With apples the correlation of crop between neighbouring trees is usually small and in such a situation multi-tree plots may have some advantages; although such experiments will always be less efficient in the use of land and material, they may save on recording labour.

This study gives no encouragement to those who might be tempted to use multi-tree plots and further reduce errors by covariance. Covariance works better on single tree plots. It can be concluded that the use of multi-tree plots cannot be justified in terms of reducing experimental error, although their use may well be required for horticultural or experimental reasons.

The results for mature trees show that it is better to conduct a trial for as few years as possible on an adequate number of trees than to attempt to reduce experimental error by lengthening the time of the trial. The only exception to this rule is that two years are safer than one because occasionally very high variation occurs within a single year.

Taking ten years' records, six years' accumulated crop adjusted by four years' accumulated crop, there is usually a reduction of the order of one-third in the coefficient of variation; only on one occasion was it reduced by half. This compares favourably with that to be expected from using ten times as many trees for a single year. With only four times as many trees the coefficient of variation should theoretically be halved. This assumes that performance of adjacent trees is uncorrelated. That this assumption is nearly true for the trial discussed here is shown by Table IV, where the closeness of the coefficients of variation to the theoretical value is evidence of a lack of correlation between adjacent trees. The assumption is further supported by the work of Pearce and Moore (1976) who, using the same data, found that adjusting by adjacent trees did not decrease crop variation.

There may be additional reasons why a trial is carried on for a number of years, the most frequent being to sample a range of years for the evaluation of treatments over this period. However, conducting a trial over a long period purely to increase its precision is not an economical measure. A better approach would be two or more short trials at different sites.

Trunk girth can be a useful adjunct to adjustment by crop but reliance should not be placed on it to reduce crop variation of well-grown apple trees. If the trees were very diverse in size then no doubt its importance would be greater.

It can be concluded that long calibration periods are wasteful and that treatments should be applied to established fruiting trees as soon as possible. There is not much difference between delaying treatments for a single year to obtain a covariate adjustment of a single year's crop and the analysis of the accumulated crop from the two-year period. With mature trees that have established a marked cropping pattern the balance of advantage would seem to lie with a single year's calibration but the experimenter is more at risk to the vicissitudes of climate.

It can also be concluded that long accumulations of crop are a wasteful method of analysing a trial. Accumulating crop for two years may be considered as a method of smoothing irregular cropping but the data presented here show little advantage over a single year's crop. Since crop is a record that must be made annually, there would seem little point in amalgamating crop records prior to statistical analysis as this would prevent consideration of the interaction of year with cropping.

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